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BATMAN Beam Properties Characterization by the Beam Emission Spectroscopy Diagnostic

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Abstract. The ITER neutral beam heating systems are based on the production and acceleration of negative ions (H/D) up to 1 MV. The requirements for the beam properties are strict: a low core beam divergence (< 0.4 °) together with a low source pressure (≤ 0.3 Pa) would permit to reduce the ion losses along the beamline, keeping the stripping particle losses below 30%. However, the attainment of such beam properties is not straightforward. At IPP, the negative ion source testbed BATMAN (BAvarian Test MAchine for Negative ions) allows for deepening the knowledge of the determination of the beam properties. One of the diagnostics routinely used to this purpose is the Beam Emission Spectroscopy (BES): the H_α light emitted in the beam is detected and the corresponding spectra are evaluated to estimate the beam divergence and the stripping losses. The BES number of lines of sight in BATMAN has been recently increased: five horizontal lines of sight providing a vertical profile of the beam permit to characterize the negative ion beam properties in relation to the source parameters. Different methods of H_α spectra analysis are here taken into account and compared for the estimation of the beam divergence and the amount of stripping. In particular, to thoroughly study the effect of the space charge compensation on the beam divergence, an additional hydrogen injection line has been added in the tank, which allows for setting different background pressure values (one order of magnitude, from about 0.04 Pa up to the source pressure) in the beam drift region.

INTRODUCTION

The requirements for the neutral beam injection system (NBI) of heating and current drive in ITER [1] are strictly demanding in order to minimize the losses along the beam line. In particular, the production and acceleration of the negative ions (H/D) is based on the negative ion source developed and optimized in the past years by IPP Garching [2]. The amount of co-extracted electrons has to be smaller than that of the extracted negative ions [3] to limit the power load on the extraction grid. Moreover, in order to limit the power losses and to increase the transmission efficiency, the ion losses by electron detachment in the accelerating region (stripping fraction) has to be limited by operating at source pressure values at 0.3 Pa maximum and keeping the beam divergence in the core (the final beam results from a large number of smaller beamlets which are formed in correspondence of the grids where small apertures are located) lower than 0.4 °[3]. Most of these requirements (not the divergence) have already been separately achieved by the smaller IPP prototypes with a smaller total voltage than envisaged for the ITER NBI system [4,5,6]; the test facility devoted to satisfy all of them simultaneously is the Neutral Beam Test Facility (NBTF) [7,8] in Padova, where the SPIDER source test facility [9] and the MITICA beam line [10] are under construction.

One of the diagnostic tools routinely used to detect the beam properties is the Beam Emission Spectroscopy (BES), providing both the estimate of the averaged beamlet divergence along the line of sight and the amount of stripping fraction by means of the H_α spectrum evaluation: the divergence can be measured from the spectral width of the Doppler shifted H_α peak, whereas the stripping fraction is obtained from the part of the spectrum between the unshifted H_α line and the shifted peak. Moreover, since the divergence of one beamlet is linked to its extracted current density (through the perveance, i.e. the beam optics) the beam inhomogeneity (i.e. the

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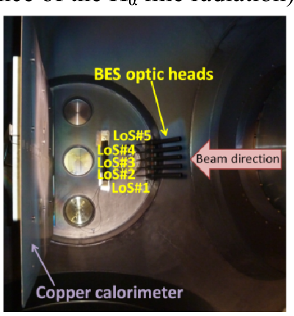
inhomogeneity of the current density distribution at the extraction) could be determined by measuring the spatial divergence distribution of the beam. For all these reasons, BES will be one of the main diagnostic in SPIDER and MITICA [11,12]. In order to find out the best method for BES data evaluation to be used in the NBTF facilities, large efforts are done in the two IPP test facilities, BATMAN and ELISE (Extraction from a Large Ion Source Experiment [13]). In particular, in BATMAN the BES system has been recently upgraded by introducing a vertical array of five lines of sight (LoSs) with the purpose to have some vertical spatial resolution.

In order to obtain a reliable measurement for the divergence (as an average along the line of sight), different algorithms and methods are under investigation, based on a simple fit (*standard* evaluation) or a parameterization method (*alternative* evaluation) [14]. The latter has been performed by means of the BBC-NI Simple code [14], even though the results are not fully encouraging: the error associated to the evaluated divergence seems to result to be too large for detecting inhomogeneity less than 10% at the given source size, since many beamlets contribute to each LoS. The only way to assess the real beam properties seems to be a forward calculation (by BBC-NI Advanced) which takes into account not only BES spectra but also all the available beam diagnostic measurements as input; this gives a real global picture of the beam, however it is time consuming and not straight-forward. An alternative way to assess the beam properties could be by means of a different code, dBES [12], which has been originally developed for the line of sight design of the BES diagnostic in SPIDER and MITICA, and which can generate BES spectra quite quickly. Although dBES cannot provide a full forward calculation on all the beam diagnostic tools, it may still be possible to extract some beam properties (e.g. divergence and stripping losses). The benchmark of dBES against BBC-NI is now under validation; the status of the benchmarking is discussed in this paper.

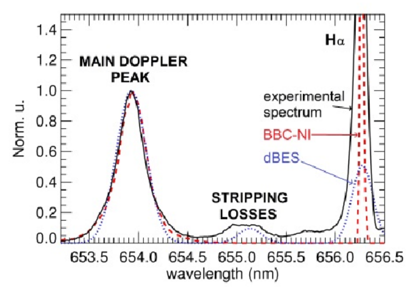
An almost complete characterization of the beam properties in a large set of different operational conditions has been recently performed, and the most meaningful results are reported and discussed in the next sections. In particular, some dedicated experiments have been performed to get information about the space charge compensation, occurring downstream the grounded grid. At the moment, in fact, it is not clear where this compensation takes place along the beam path but this information could be of importance for a realistic simulation of the beam line (i.e. by BBC-NI Advanced or other codes). In the last sections, we report about the effects of the space charge compensation on the BES spectra in BATMAN: some preliminary results and considerations are then discussed.

THE NEW BES DIAGNOSTIC IN BATMAN

The new BES system in BATMAN is based on a vertical array of 5 horizontal LoSs looking in the counter-beam direction. This new system replaces the previously installed vertical pair of horizontal LoSs (one 15 mm above the equatorial plane of the tank, the other one 50 mm below it), which were looking at the beam throughout a window with an observation angle (with the beam direction) of 63° and 61°, respectively. However, only two LoSs could not permit to obtain any significant result in terms of spatial resolution. The new system, whose optics heads are installed inside the vacuum tank as shown in Figure 1(a), are instead vertically uniformly arranged (from 80 mm below the tank equatorial plane for the LoS#1 up to 80 mm above it for the LoS#5), thus permitting to discriminate possible vertical differences. The light collected by each LoS comes from different beamlets (in BATMAN the whole beam is composed by the superimposition of 126 beamlets). The BES optics heads are set at about 1.2 m downstream of the plasma grid and look with an angle of 57° (blue shift of the Doppler shifted peak). The optics heads house a 20 mm diameter lens each: it collects the light into an optic fiber (400 μm-core diameter) which is connected to a multi-channel Andor spectrometer (wavelength range 300-800 nm; wavelength resolution 12 − 15 pm/pixel and instrument profile of 0.106 nm in correspondence of the H_α line radiation), equipped with an Andor CCD (26.6 x 6.6 mm / 1024 x 255 pixel). To



(a)



(b)

FIGURE 1. (a) Set up of the BES optical heads in BATMAN. (b) Example of a BES spectrum obtained in BATMAN (pulse #97721 in hydrogen, LoS#3, extraction voltage 4.67 kV, acceleration voltage 15.16 kV) compared to the spectra simulated by BBC-NI simple and dBES.

have good signal to noise ratio, the exposure time of the CCD is usually set to 1 s.

An example of a BES spectrum obtained in BATMAN is displayed in Figure 1(b). The unshifted H_α peak is on the right side, at 656.28 nm; the main Doppler shifted peak is centered at around 653.9 nm according to the total voltage (U_{tot} = 19.9 kV), while its shape and width is determined by the angular distribution of the beam particles seen by the LoS. The stripping peak is in between the unshifted and the main Doppler peak. In the example of Figure 1(b), the peak associated to the stripping particles is around 655.3 nm, corresponding to a Doppler shift related to the velocity gained by the extraction voltage U_{ext} (4.67 kV), and indicating that the large part of stripping particles has its origin at the end of the gap between the extraction and the grounded grid. This is due to the combination of a high background gas density and a high collision cross section. However, it is worth noting that their contribution can extends even at much lower wavelength so that they could overlap with photons belonging to the right wing of the main Doppler peak. All these aspects must be taken into account for the estimation of the divergence and of the stripping fraction.

BES spectra evaluation

In order to provide a reliable measure of divergence, different methods to analyze the data have been investigated. So far, a *standard* evaluation based on the Gaussian fitting of the central part (above 30% of the maximum) of the main Doppler shifted peak has been performed successfully in IPP small prototypes [15,18]. This method is based on the assumption that the main Doppler shifted peak originates only from fully accelerated radiating particles, so that the different directions of the particles due to the divergence of the beamlets contribute to the broadening of the Doppler peak (the instrumental and geometrical effects contributing to the width of the main Doppler peak are taken into account and subtracted). As shown in Figure 1(b) the main Doppler peak presents two large wings at both sides: this is assumed to be caused by a “halo” consisting of particles with relatively larger trajectory angles but with a small contribution. The majority of the radiating beam particles are instead from the core of the beamlets (corresponding to smaller radiating angles) which generate the central part of the main Doppler shifted peak. Divergence is then defined as the half e-folding width of the main Doppler shifted peak, as results from the Gaussian fit. In the *standard* evaluation method, the stripping fraction is evaluated by integrating the spectrum in an interval of ±0.25 nm around the wavelength corresponding to U_{ext}; this integral is then compared to the one of the full energy peak, keeping the cross section and the velocity of the particles into consideration. The choice of the interval of integration for the stripping losses is critical. The broadening of the stripping particle comes from a convolution of their angular distribution (which can be different from the one of the fully accelerated beam particles) with the distribution of the kinetic energy of the particles when the electron is stripped. Since the cross sections for excitation are almost constant in the energy range, an average cross section can be considered. In this way, however, the measured stripping fraction in the IPP prototype results to be at least two times lower than the value predicted by models [15,18]. However, when operating close to the optics optimum, the standard evaluation of both divergence and stripping fractions is anyway a good approximation.

To improve the evaluation of the divergence and the stripping fraction, an *alternative* method for the BES data interpretation has been developed [14], tested in BATMAN and in ELISE. A simulation program (BBC-NI) is used to reproduce the BES spectrum under different beam conditions. In particular, the divergence ε of the beamlets and the extraction and acceleration voltages (U_{ext} , U_{acc}) were changed during different simulations in order to cover the typical operative scenarios of BATMAN. For each produced spectrum the full energy peak is fitted with a user defined function F to measure its spectral width w (which clearly depends on the definition of F). At this point an empirical function g is determined so that $\varepsilon = g(w, U_{ext}, U_{acc})$. After some preliminary studies g was defined as three nested linear functions: $\varepsilon = mw+t$, with coefficients m and t linearly depending on U_{ext} with coefficients linearly dependent on U_{acc}. The final form of g contains some constants set to best fit g to the inputs (ε, U_{ext}, U_{acc}) and the outputs (w) of the simulations. The values of the constants depend on the LoS considered: the position of the LoS indeed influences the angular distribution of the collected photons and therefore the shape of the spectrum. At last, the function g is evaluated when a BES spectrum is experimentally collected: the full energy peak is fitted with F and the resulting value of w is used to obtain the divergence (U_{ext} and U_{acc} are known from the operational settings).

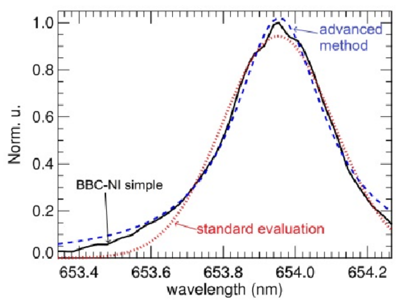
Simulation of the BES spectra: two codes

The alternative method for the divergence estimation in BATMAN has been developed by means of the BBC-NI code in the “simple” mode [14]. The program simulates each beamlet with a bunch of particles starting at the grounded grid and takes only the fully accelerated negative ions into account. The trajectories of the particles have a Gaussian angular distribution with respect to the axis of the beamlet. More specifically, the direction of each particle is set in terms of the azimuthal and polar angles (γ_a, γ_p):

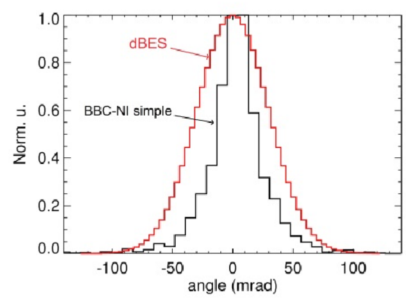
$$\gamma_a = \varepsilon \cdot erf^{-1}(z_1)\ ;\ \gamma_p = 2\pi \cdot z_2 \tag{1}$$

where ε is the e-folding value of the divergence and z_1 and z_2 are two random numbers uniformly distributed in the interval [0,1]. A forward calculation makes the trajectories evolve and checks at each time step for possible interactions between the particles and the background gas; only the H_α photons emitted in the volume of the LoSs are considered, and are simulated as the isotropic emission of a number of "mini-photons" to detect a sufficient amount of photons to decrease the statistical noise (saving computation time). The mini-photons effectively collected by the BES optics contribute to the simulated spectrum with Gaussians whose centroid is given by the particle-photon angle and whose width is given by the instrumental profile of the spectrometer. Since the calculations start just after the acceleration phase, no electric field is considered; in this way only the main Doppler shifted peak and the unshifted H_α peak are simulated. BBC-NI Simple is used to get a better understanding of the formation of the main Doppler shifted peak in a BES spectrum, and it is suitable to study inhomogeneous distributions of the accelerated current density. An example of a spectrum produced by BBC-NI simple is shown in Figure 1(b); the input value of ε was determined with the standard evaluation applied to the experimental spectrum (shown in the same figure). As it can be seen, the simulation reproduces the non-Gaussian slope of the left side of the main Doppler peak. The right side is quite well reproduced too; in general however this may not be always the case because the right side of the main Doppler peak is partially superimposed to the contribution of the stripping losses [14].

The analysis of the spectra produced by BBC-NI simple showed that the left side of the main Doppler shifted peak can be reproduced better by a Lorentz curve rather than the Gaussian shape used for the standard evaluation (see Figure 2(a)) of the standard evaluation. The Lorentzian profile was then chosen as function *F* to retrieve the values of *w* for the parameterization method. A set of representative configurations of the source were simulated. The parameterization method then proved to be self-coherent over a large number of other spectra produced by BBC-NI.



(a)



(b)

FIGURE 2. (a) Full energy peak in a BES spectrum produced by BBC-NI (same pulse of Figure 1(b)), analyzed with the standard and advanced methods; the spectrum produced by dBES coincides with the curve of the standard evaluation. (b) Angular distribution of the particle velocities for BBC-NI Simple and dBES.

A critical aspect in the parameterization method is the error associated to the divergence evaluation. Even though it results to be smaller than the one found in the *standard* method, it remains larger than 15% due to the approximations done in the parameterization functions used. In the perspective of calculating the homogeneity of the beam (i.e. of the current density) from divergence measurements (the intensity of the beam influences the beam optics), this is not acceptable because the target defined by ITER on the beam homogeneity uncertainties is 10% [14]. This suggests that the present parameterization method is still not sufficient for the determination of the beam inhomogeneity with a BES line-of-sight array. However, the reliability in terms of a detected divergence profile seems to be more promising than what expected: even in presence of large errors, trends with the source parameters and relative patterns are reliable. The parameterization method has been already successfully benchmarked for BATMAN, and it is going to be adopted for all the five LoSs; the results reported in this paper have been performed with the *standard* method.

A second code simulating BES spectra and possibly suitable for the parameterization method is under investigation. This is the dBES analytic code [12] developed at Consorzio RFX in Padova. dBES is not a Monte Carlo simulation but it calculates the particle density of the beamlets, i.e. assuming that the transversal power density distribution of each beamlet is Gaussian according to models adopted by ITER [3]:

$$P(\omega)/P_{\max} = \frac{1-f}{\pi(X\varepsilon_{beam})^2} e^{-\left(\frac{\omega}{\varepsilon_{beam}}\right)^2} + \frac{f}{\pi(X\varepsilon_{halo})^2} e^{-\left(\frac{\omega}{\varepsilon_{halo}}\right)^2} \tag{2}$$

where *X* is the distance from the grounded grid, ω is the angle with respect to the beamlet axis, *f* the fraction of halo and ε_{beam} and ε_{halo} are the e-folding divergences of the nominal and halo components of the beamlet. At the moment the "halo" experimentally observed as in Figure 1(b) is not considered in the code; dBES assumes ε_{beam} and the energy distribution of the particles as input data and calculates the intensity of the collected light according to the geometry of the beamlets, the various emission cross sections and the characteristics of the optics. The width of the peaks in the simulated spectra is determined analytically by the divergence and other broadening factors like the instrumental profile of the spectrometer and the angle under which the emitting particles see the lens. The physical model related to the broadening of the spectral lines is used also by dBES for the standard evaluation method, to calculate the divergence and its error. More details can be found in [12]. The code has been developed for the optimization of the line-of-sight geometry for NBI systems equipped with a BES diagnostic tool. At present, the benchmark of dBES with BBC-NI and BATMAN experimental data is in progress. The algorithm of dBES is such that the shape of the simulated full energy peak is identical to the curve of the standard evaluation (see Figure 2(a)), i.e. Gaussian. The spectra produced by dBES and BBC-NI Simple have peaks with slightly different shapes because the beamlets are simulated differently: in BBC-NI (Eq. 1) the angles of the particle trajectories respect to the beamlet axis follow a Gaussian distribution (see Figure 2(b)); the resulting power density distribution is steeper and narrower than the original Gaussian: this explains the choice of the Lorentz curve for the fit of the spectra. dBES instead adopts a Gaussian curve (Eq. 2) for the power density profile, so that the angular distribution of the beamlet particles is for dBES of the type shown in Figure 2(b). Comparing the results of the two codes with the spectra of Figure 1(b), the results of BBC-NI Simple seem to best fit the experimental curve; however the possible presence of halo and beam aberrations makes difficult to take an *a posteriori* definitive choice of the beamlet model only on the base of the BES spectra. The solution of the issue will certainly require the help of programs capable of simulating the production and the acceleration of the H^- ions, as planned for BBC-NI Advanced, where all the information coming from different beamline diagnostics (BES, calorimeter) are included. However, several realistic information on the beam are still missing, among which the location where the space charge compensation occurs along the beam path; this leads to a not yet fully successful beam property evaluation.

BATMAN BEAM PROPERTIES CHARACTERIZATION BY BES

Beyond the numerical studies to reproduce and better analyze the BES spectra, an extensive investigation of the beam properties with the new BES system has been recently carried out in BATMAN; the BES data evaluation has been performed with the standard evaluation: even though the absolute value for the estimated divergence is not the best estimate and the errors could be too large, its spatial pattern and its trends while changing the source parameters are reliable.

An example of the bias current (I_{bias}) dependence of the beam characteristics with the external magnet frame for the filter field (with the external frame, a vertical beam deflection due to the magnetic field is observed) is displayed in Figure 3. In panel (a), the typical current dependence on I_{bias} [16] is shown: the increase of the bias current drastically decreases the amount of co-extracted electrons; the extracted ion current decreases less and at higher bias current. Usually BATMAN operates with a bias current of 11-15 A, where the reduction of co-extracted electrons (j_e) is high while the ion current (j_{ex}) is still around its maximum.

The corresponding divergence estimation for these experiments, evaluated using the thermocouples installed on the standard copper calorimeter is displayed in Figure 3(b), both for the horizontal and vertical directions.

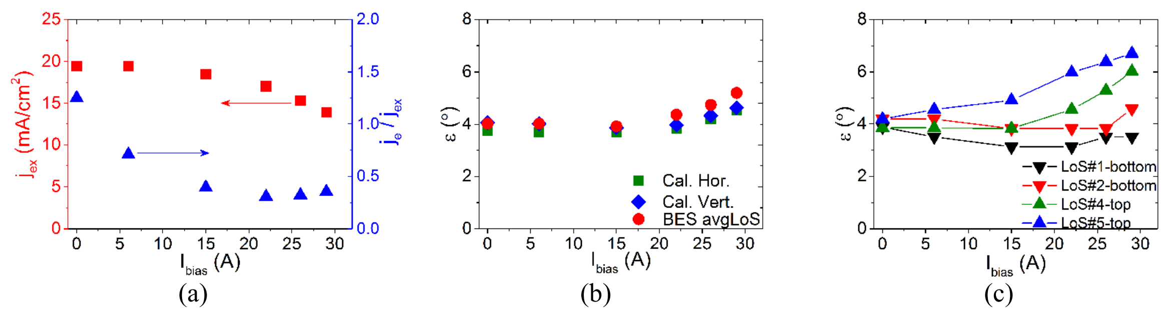


FIGURE 3. (a) Current density characterization with I_{bias} dependence (U_{ext} = 4.6 kV, U_{acc} = 10.2 kV). (b) Divergence estimation from the copper calorimeter (horizontal and vertical direction) and the BES system. Divergence by BES is averaged on four LoSs. (c) Vertical profile of the divergence, as evaluated by BES.

The calorimeter divergence is obtained by means of the DENSB code [17] with a parameterization method: the Gaussian fit of the experimental thermocouples data permits to estimate the beamlet divergence; the calorimeter divergence estimation is found to be well correlated to the one from BES, as displayed in

Figure 3(b) (here for BES the average value of four LoSs; the central LoS#3 was not available). For both the diagnostics, an increase in the divergence is observed in correspondence of the bias current increase, associated to a smaller normalized perveance value (these experiments have been performed in the under-perveant region: smaller normalized perveance means larger divergence).

The spatial pattern of the divergence in the vertical direction of the beam is shown in Figure 3(c). In the unbiased pulse divergence is almost constant throughout the whole beam; as soon as the bias current increases a clear pattern is observed: the divergence averaged on the two LoSs looking at the lower part of the beam (LoS#1 and LoS#2) do not vary while the divergence for the two LoSs looking at the upper part of the beam (LoS#4 and LoS#5) largely increases with I_{bias}. This suggests a different behavior for the upper and the lower part of the beam. It is worth noting that the smaller values for the divergence at high bias are in correspondence of the LoS#1 and LoS#2 (bottom); for these pulses downwards is also the deflection of the beam due to the magnetic filter field so that LoS#1 and LoS#2 are looking at the beam core.

Such different spatial beam properties in the upper and lower part of the beam have been observed in a large number of operational conditions, especially at high RF power. We can exclude that the difference comes out from the BES data analysis method (a sort of aliasing or artefact), since in beam pulses with identical operation conditions but a reversed beam deflection a reversed asymmetry is found. An example of the divergences evaluated by BES in two identical pulses but with reversed beam deflection is displayed in Figure 4(a). In all the experimental conditions investigated, divergence values are lower in the part of the beam where the filter field deflects the beam while larger divergences are associated to the remaining half. In addition, the BES spectrum intensity (see Figure 4(b)) for the more external LoSs (#1 for an upward beam deflection, #5 for the downward one) is much lower than for the other LoSs, probably due to the fact that only photons from particles with very large divergence and belonging to beamlets far away from the LoSs itself are collected resulting in a very large divergence [14] for LoS#1 (deflection up) and LoS#5 (deflection bottom).

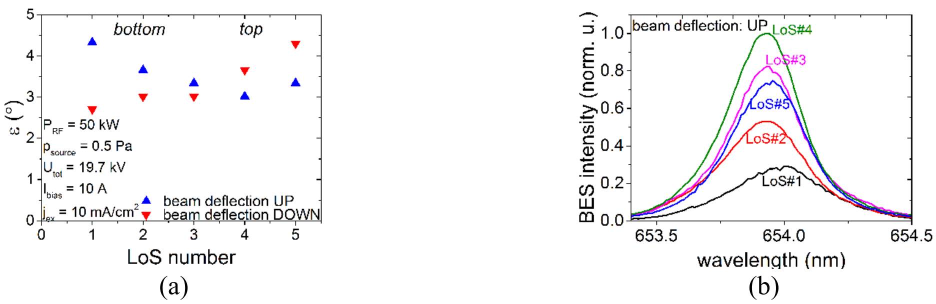


FIGURE 4. (a) Vertical beam divergence profiles for similar pulses with reversed beam deflections: up (#97482) and down (#98460). (b) BES intensity (normalized to one) for the main Doppler peak (pulse #97482 of panel (a)).

The reason for such a spatial profile in the divergence could be related to a local perveance variation: a slightly higher perveance, and therefore smaller divergence moving towards the optimum perveance, could be found in the part of the beam corresponding to the beam deflection. This would therefore imply a slightly different extracted current density for the upper and lower grids, in relation to the deflection direction.

No evidences of current density inhomogeneity have ever been observed in BATMAN, neither by BES nor by the standard copper calorimeter. Regarding the BES system, the two LoSs available until last year were looking not separately to the two different part (upper and lower) of the beam (i.e. grids), so that a net difference in the evaluated divergence was not detectable. As concerns the copper calorimeter, the reason seems to lie in the fact that it is so far away downstream the grounded grid (1.7 m) and the beamlet divergences are in general so large (more than 2-3°deg) that the beam inhomogeneity at 1.7 m is smoothed so much that the spatial resolution of the thermocouples on the copper calorimeters is not enough to detect it. Simulations (with different codes) of the beam power deposition on the copper calorimeter are still under investigation.

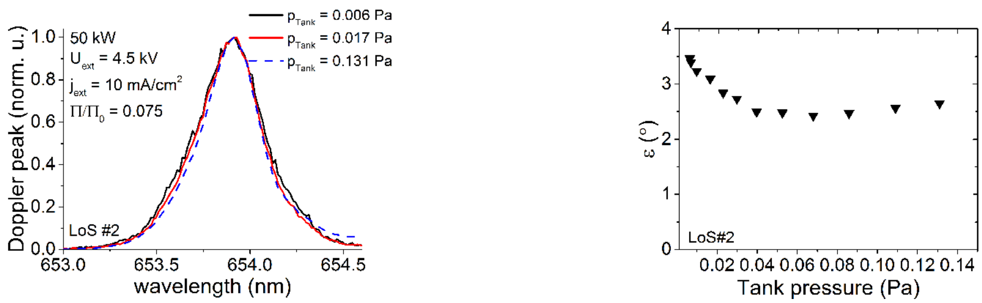
An inhomogeneity in the BATMAN beam power has been instead recently detected by the mini-STRIKE calorimeter [19], which has temporarily replaced the standard copper one, and which is placed only 1 m downstream the grounded grid. Further details on this kind of measurements and results can be found in Ref. [20]. The physical reason for such current density inhomogeneity is not yet clear: at the moment, the most reliable hypothesis is associated to the non-optimal source conditioning in some particular experimental conditions, but further investigations and simulations for explaining it are ongoing work.

EFFECTS OF SPACE CHARGE COMPENSATION ON BES SPECTRA

In order to bring modeling close to the experiments (as mentioned at page 5) it is necessary to add as inputs for the codes as many information as possible coming from all the available beam diagnostics. At present, one of the information missing is where the space charge compensation effect of the beam takes place along the beamline. In order to investigate this effect in BATMAN, a dedicated hydrogen gas line has been added to the tank, at about 0.4 m downstream the grounded grid. This line provides a constant flow of H_2 through a valve in correspondence of the equatorial plane of the tank. The pressure measurement in the tank is provided at about 1 m downstream the grounded grid. The pumping system in the tank consists of two turbo molecular pumps (both in correspondence of the copper calorimeter: one at the top of the tank and one lateral) and a titanium pump at the bottom of the tank. A pressure gradient along the beam trajectory is expected but not considered relevant for the following analysis; the possible presence of a vertical pressure gradient inside the tank due to the pumping system will be shortly discussed later on.

The tank pressure has been varied in these experiments: for all the pulses the beam optics was kept constant (same perveance) for the measurements on the beam. The titanium pumps have been operated between pulses in order to recover a good vacuum in the tank in between two consecutives pulses, and to better control the pressure tank increase due to the H_2 gas inflow. The pressure in the tank ranges in between 0.006 – 0.13 Pa in the considered experiments; larger pressures in the tank would lead to breakdowns in the grid system. The errors in the absolute number of the pressure measurements are quite large due to the calibration of the pressure system, but reliable in relative.

The tank pressure increase shows clear effects on the BES spectra: the fraction of the stripping linearly increases (not shown here) and the width of the Doppler decreases.



(a) (b)

FIGURE 5. (a) Main Doppler shifted spectra (normalized to one) at different tank pressures, for the LoS#2. (b) Divergence estimation for the LoS#2, as a function of the tank pressure.

The narrower width of the main Doppler shifted peak at high pressures is evident for the LoSs looking at the beam in correspondence of the downward beam deflection (LoS#2 for these experiments). An example of the main Doppler shifted peak spectrum for the LoS#2 at three different tank pressures is shown in Figure 5(a): the lowest (0.006 Pa) and the highest pressure value achieved (0.131 Pa) are displayed together with the spectrum in correspondence of an intermediate pressure value (0.017 Pa). The shifted peak at the lowest pressure is clearly larger than the others (even though the signal to noise ratio is small due to the low pressure in the tank); the spectrum corresponding to the larger pressure value is the narrowest one; the intermediate curve corresponds to the intermediate pressure value. The divergence evaluated with the *standard* method for the LoS#2 as a function of the tank pressure is displayed in Figure 5(b): divergence clearly decreases with the increase of the pressure in the tank, reaching a minimum in between 0.04-0.06 Pa. A slight divergence increase for the highest pressure value is observed, but this is due to the operational difficulties of keeping the same beam optics. Similar patterns are found for four LoSs (#1 - #4), while for the LoS#5 (at the top) the effect is almost negligible. It could be related to the fact that this LoS is the farthest away from the beam core, but this is still an open issue. The minimum of the divergence is found to be at the same pressure value for all the four LoSs in which this phenomena is observed: this could imply that there are no vertical pressure gradients inside the tank playing any role on the divergence calculation for these experiments.

In order to determine the critical neutral density at which space charge compensation occurs, a simple model [21] has been used. However it appeared that values of the beam radius (left as free parameter) that had to be used to match the experimental density measured in this paper were out of the range expected for BATMAN. This suggests that more sophisticated models should be used.

SUMMARY

The divergence and stripping particle fraction estimation from BES spectra is not straight-forward, and big efforts in code development are needed for their evaluation with accuracies satisfying ITER requirements. It has been shown, as an example, that divergence cannot be evaluated by a simple Gaussian fit of the main Doppler shifted peak in BATMAN, since Lorentzian tails due to halos are present in the spectrum and stripping particle photons affect the low energy side of the main Doppler peak. Only forward calculation could therefore permit to access the real beam properties. The code used in the last years for this kind of investigation in BATMAN is BBC-NI: an updated version with a parameterization method has been developed and is going to be applied to the BATMAN BES spectra. At the moment, a second code (dBES) is also under investigation for the parameterization method, and it is being benchmarked in BATMAN.

However, even though the divergence absolute values evaluated so far with the standard are affected by too large errors, the trends on the operational source parameters and the spatial patterns obtained are valid anyway.

In order to improve the information of the beam properties, the BES system in BATMAN has been recently upgraded, with the installation of five LoSs which permit to have vertical spatial resolution. A previously unobserved vertical profile of the divergence is found: it results smaller in correspondence of the direction of the beam deflection due to the magnetic filter field with respect to the other half of the grid. The asymmetry between the upper and lower part of the beam reverses when the beam deflection is reversed (i.e. the filter field magnet frame). The reasons for such vertical beam inhomogeneity must be further investigated but could be related to a non-optimal source conditioning.

Dedicated BES measurements in which the gas pressure in the tank has been varied (by about 2 orders of magnitude) have permitted to observe the effects of space charge compensation on the BES main Doppler peak spectrum. The shifted peak width decreases with the tank pressure and saturates at a pressure of 0.04-0.05 Pa. This pattern is observed for four LoSs (1-4), while for the fifth one the effect seems to be negligible. This could not be related to the presence of a pressure gradient since the other four LoSs saturate all at the same pressure value but it may be related to the vertical deflection of the beam due to the filter field (the intensity of this LoSs is low being the farthest away from the beam core); further investigations are ongoing work.

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